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Hurricane Ivan's Impact Along The Northern Gulf Of Mexico

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Just over a year after the landfall of Hurricane Ivan, scientists have now had an opportunity to evaluate a variety of oceanographic and geologic responses to this storm. Hurricanes Ivan, Katrina, and Rita are among the most powerful hurricanes recently to enter the Gulf of Mexico.

Although it weakened from a very powerful Category 5 hurricane to a Category 3 before making landfall along the Alabama coast, Hurricane Ivan devastated the coasts of northwestern Florida and Alabama on 16 September 2004. This article summarizes what researchers have learned about Hurricane Ivan as it moved into the Gulf and made landfall along the northeastern Gulf of Mexico coast. The article focuses on storm meteorology, sea state, shelf circulation, and sediment transport on the shelf and along the coast.

Meteorological and Oceanographic Characteristics

While in the northwest Caribbean Sea, Ivan's minimum central (or sea level) pressure, P_o, was below 920 millibar (mbar), which placed it as a Category 5 over Jamaica. After entering the Gulf of Mexico, P_o ranged from 924 to 939 mbar (Category 4). In addition, while crossing the Gulf of Mexico, the hurricane's wind speed 10 meters above the sea surface dropped slightly, from 64 to 57 meters per second, as estimated by the U.S. National Hurricane Center (NHC).

The maximum extent of wave heights can be estimated by the severe wave damage to numerous oil and gas platforms offshore, which was observed at some 27 meters above sea level (for actual footage of Ivan's waves, see http://www.wavcis.lsu.edu). East of the mouth of the Mississippi River, a National Data Buoy Center (NDBC) buoy (Figure 1) measured 16.8-meter-high waves, the second highest ever recorded during a hurricane; Katrina measured 17.91-meter-high waves at the same buoy. East of the Chandeleur Island arc along southeastern Louisiana, waves approximately 7.6 meters high were recorded as Ivan veered to the north-northeast prior to landfall. Although downgraded to a Category 3 hurricane at landfall east of Gulf Shores, Ala., a storm surge along the open coast in excess of three meters was measured; breaking waves of 3.5–4 meters were likely, according to numerical hindcasts.

Impacts on Shelf/Slope Circulation and Temperature Change

Real-time satellite measurements from multiple sensors, which were received by

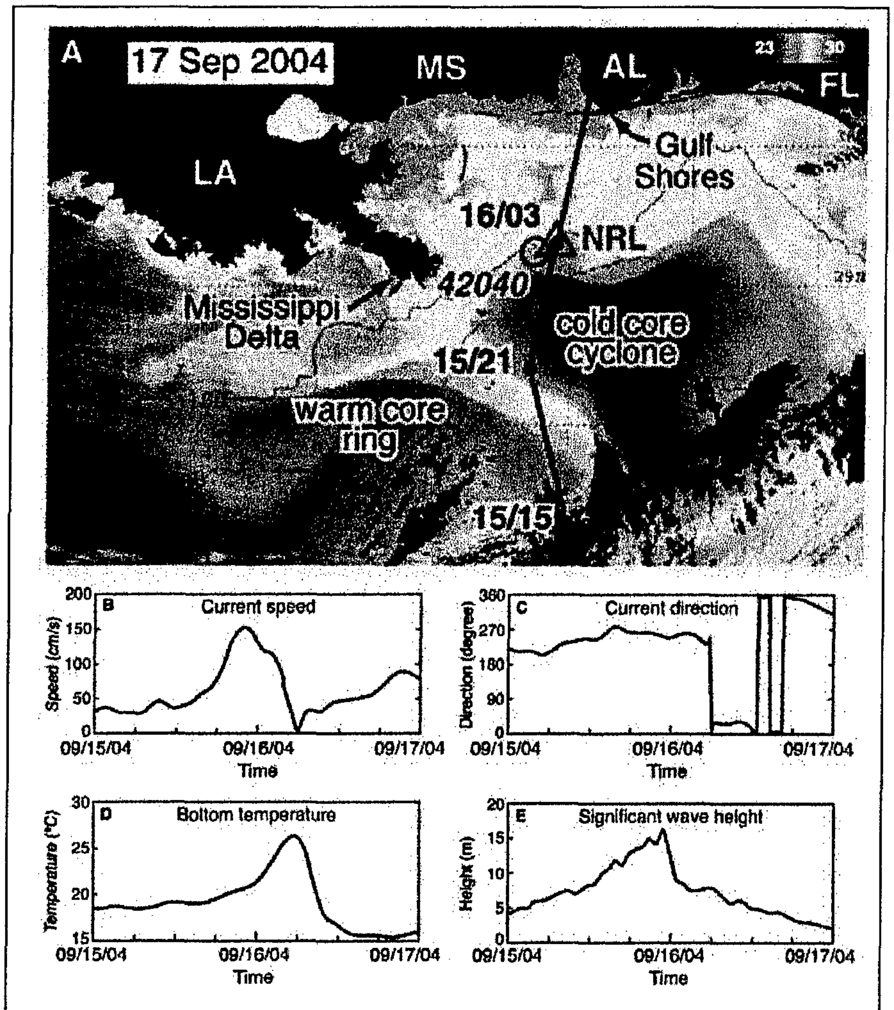

Fig. 1. (a) MODIS nighttime sea surface temperature (°C) composite image of 16–17 September 2004 showing a large area of cooling (< 26°C) within a cold core cyclone southeast of the Mississippi delta. Ivan's six-hourly positions are shown along its track (red dots/lines). The Naval Research Laboratory mooring is depicted with a triangle, and NDBC buoy 42040 is depicted as an open circle. The 100- and 1000-meter isobaths are shown with solid lines. (b) Current speed (centimeters per second). (c) Current direction (degrees). (d) Bottom temperature (°C). (e) Significant wave height (meters) in 89 meters of water from 15–17 September 2004.

By G. W. Stone, N. D. Walker, S. A. Hsu, A. Babin, B. Liu, B. D. Keim, W. Teague, D. Mitchell, and R. Leben

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Louisiana State University's Earth Scan Laboratory (http://www.esl.lsu.edu), enabled hurricane tracking as well as the rapid surveillance of coastal and ocean responses along its track.

The Moderate Resolution Imaging Spectroradiometer (MODIS) nighttime sea surface temperature image composite of 16–17 September 2004 revealed sea surface cooling of several degrees under and east of Ivan's track in water depths exceeding 1000 meters (Figure 1a). Satellite altimetry data indicated that this cool feature was located in a large area of cyclonic circulation, southeast of the Mississippi delta. *Walker et al.* [2005] showed that the hurricane wind field energized the cyclone, enhancing upwelling of its relatively shallow thermocline.

Hurricane Ivan passed directly over the shelf and slope moorings of the U.S. Naval Research Laboratory's (Stennis Space Center, Miss.) Slope to Shelf Energetics and Exchange Dynamics project. This allowed current meter data (current speed and direction) to be obtained from 14 project moorings west of the DeSoto Canyon. Figures 1b and 1c show current speed and direction 10 meters below the surface and bottom temperature change (Figure 1d) at the site on the 89-meter isobath.

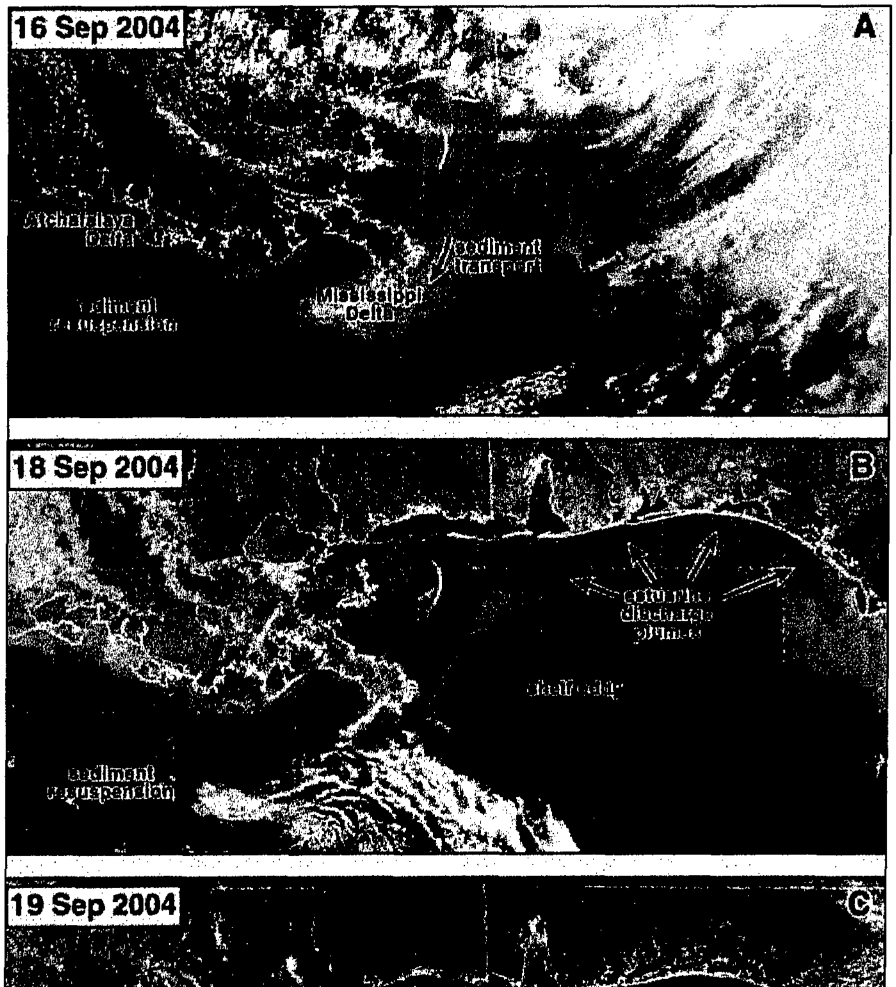

Fig. 2. Time sequence of "true color" imagery from the MODIS and OCM (Ocean Color Monitoring) 250–500 meter resolution (red, green, blue) bands on (a) 16 September 2004 (MODIS); (b) 18 September 2004 (OCM); and (c) 19 September 2004 (MODIS). Events and processes discussed in the text are annotated on the figure.

Hurricane-force winds strengthened westward flow from 50 to 150 centimeters per second. Also, bottom temperatures initially increased from 18°C to 26°C, as warmer surface waters were mixed downward. After the hurricane passed on 15 September, current speeds decreased, current direction changed, and bottom temperature rapidly cooled from 26°C to 15.2°C. The cool, bottom water is believed to have upwelled from depths exceeding 200 meters along the northern flank of the cyclone and was responsible for the temperature decrease.

The MODIS image from 16 September (Figure 2a) revealed a large mass of sediment flowing southward along the east side of the Chandeleur Islands and Mississippi delta. In this same area, extensive damage occurred to submerged oil and gas pipelines from bottom sediment movements (*Wall Street Journal*, 2004; http://www.mms.gov). Strong current jets have been reported previously in the aftermath of storm events at the Mississippi delta [*Walker et al.*, 1996].

Estuarine discharge plumes extended 20–30 kilometers into the Gulf, and algal blooms were observed along their outer margins. Large-scale sediment resuspension was detected on the Louisiana shelf as far west as the Atchafalaya Bay (Figures 2a and 2b).

NDBC buoy 42040 (initially moored at 29.22°N, 89.2°W) broke free from its mooring on 15 September. Its path, tracked by satellite, revealed a major avenue for the off-shelf transport of shelf water between the cyclone and anticyclone southeast of the Mississippi delta (Figure 2c).

Metocean Characteristics and Model Verification

Figure 1 shows that Ivan's eye was very near NDBC buoy 42040 at 0300 UTC on 16 September. This provided an excellent opportunity to further verify the practical formula for estimating significant wave height from minimum pressure. According to *Hsu et al.* [2000],

$$H_{smax} = 0.2\,(1013 - P_o), \qquad (1)$$

where H_{smax} is the maxim significant wave height and P_o is the minimum central (or sea level) pressure. From Figure 1, between 2100 UTC on 15 September and 0300 UTC on 16 September, the estimated P_o = 933 mbar. Substituting this into equation (1), H_{smax} = 16 meters. This result is in excellent agreement with the maximum value of 15.96 meters as measured by buoy 42040 at 0000 UTC on 16 September (see the NDBC Web site at http://www.ndbc.noaa.gov).

During the same six-hour time period (before the buoy broke loose from its mooring), wind speed at five meters above sea level was approximately 27 meters per second. This value was only 46 percent of the 59.3 meters per second reported by NHC (Figure 1). Therefore, the wind measurements at buoy 42040 during this time period near landfall could not have generated the 16-meter significant wave height at this location. The 16-meter waves were induced by the P_o at a much earlier

time. Thus, caution needs to be exercised in relating the wind speed measurements at landfall to determine wave conditions.

Buoy 42003 was also under the influence of Ivan for several hours, as shown in Figure 1. From the NDBC record, the maximum significant wave height was measured around 0100 UTC 15 September when the buoy was located in the northeast quadrant of Ivan. Pertinent data records for open-coast wave characteristics are significant wave height (H_s) and dominant wave period (T_p). Dominant wave period is the period with maximum wave energy (see the NDBC Web site). Maximum H_s = 11.04 meters and T_p = 12.9 seconds were recorded at buoy 42003 during 0100 UTC.

With these data, the following formula can be validated. According to *U.S. Army Corps of Engineers* [1984, p. 3-85, equation (3-64)],

$$T_p = 12.1\sqrt{\frac{H_s}{g}}, \qquad (2)$$

by substituting H_s=11.04 meters into equation (2), then T_p=12.8 seconds, which is in excellent agreement with the measured T_p = 12.9 seconds. Note that equation (2) has also been verified during Hurricane Georges [*Hsu et al.*, 2000].

Geological Impacts

Beach erosion along the Louisiana (Chandeleur Island), Alabama, and northwestern Florida coasts was severe. Barrier islands were overwashed and breached extensively, and dunes with pre-storm elevations of 3.5 meters were reduced to sea level (Figures 3a and 3b). Beach width loss of greater than 50 meters was measured along the Florida Panhandle near Pensacola Beach (Figures 3a and 3b).

Remarkably, however, many of the barrier islands in this area did not lose considerable amounts of sand because beach and dune sediment was transported across the islands as large overwash fans whose marginal lobes prograded (landward edges migrated bayward) the back-barrier beach over 100 meters into the adjacent bay (Figure 3). This phenomenon, referred to as "conservation of barrier mass," was also measured after Hurricane Opal, a powerful storm that affected the Florida Panhandle in 1995 [see *Stone et al.*, 1996, 1999].

Aerial reconnaissance immediately after Ivan revealed that portions of many of the barrier islands (e.g., Santa Rosa Island as shown in Figure 3c) were entirely submerged during the storm. Large bed forms with wavelengths of 15–20 meters and amplitudes of between 1 and 1.5 meters were observed periodically along these barriers, indicating considerable wave-induced turbulence during the event (Figure 3c). Considerable structural damage occurred to beach homes and condominiums along the coast as well as to road, bridge, and highway infrastructure connecting the mainland to the outer coast.

What Have We Learned From Ivan?

Several important conclusions can be drawn from this work. First, Earth-orbiting satellites provided a valuable time sequence of images. Those images revealed a range of extreme

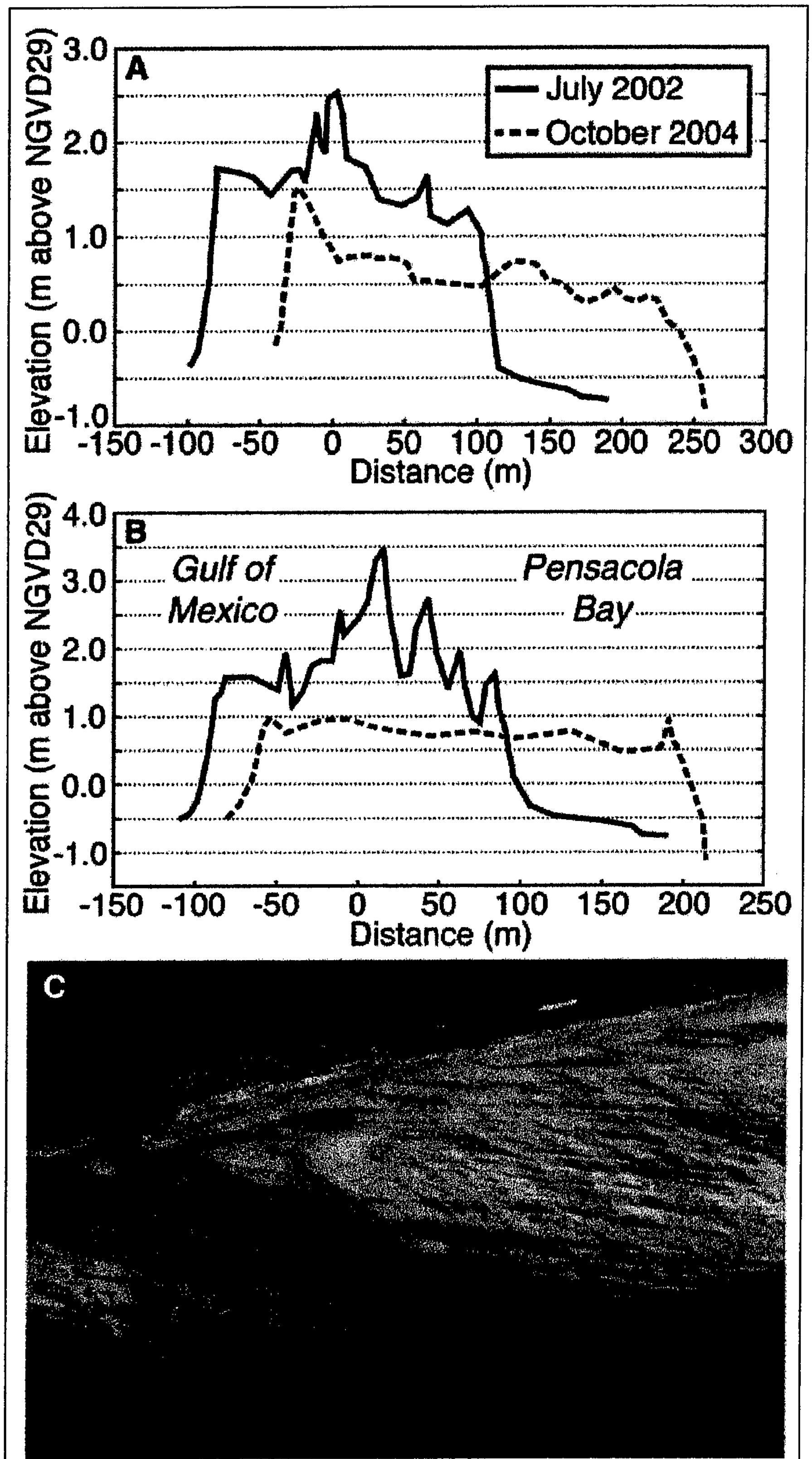

Fig. 3. (a and b) Comparison of pre- and post-Hurricane Ivan profiles taken on western Santa Rosa Island, Fla. Note the erosion-deposition couplet where eroded sand from the nearshore-beach foredune is transported across the island and deposited as a large overwash deposit. Data indicate that this portion of the barrier "conserved mass" during Ivan. (c) Large-scale bed forms occurred on the same island during Ivan. The features are approximately 15–20 meters in length and between 1 and 1.5 meters in amplitude.

circulation events along the coast and offshore, which aided the understanding of field measurements and the damages to oil and gas facilities. In addition, the operational formulae, such as equation (1) for estimating the maximum significant wave height from minimum sea level pressure during a hurricane, were further verified.

Also, the ideal location of the mooring on the Mississippi shelf relative to the track of Ivan allowed new insight into the current and temperature field. Additionally, the "conservation of barrier mass" concept, which was noted for previous historic events such as Opal in 1995, was further verified for Ivan.

While Ivan did not produce extensive storm surge when compared to, for example, Katrina, extremely high waves resulted in extensive scour along the most severely affected structures located on the open coast and in bays. Given the likelihood that the southeastern United States is currently in a multidecadal period during which storms more intense than Ivan (e.g., Katrina) may occur more frequently, future societal implications associated with these events are enormous.

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References

Hsu, S. A., M. F. Martin Jr., and B. W. Blanchard (2000), An evaluation of the USACE's deepwater wave prediction techniques under hurricane conditions during Georges in 1998, *J. Coastal Res.*, *16*(3), 823–829.
Stone, G. W., J. M. Grymes III, C. K. Armbruster, J. P. Xu, and O. K. Huh (1996), Researchers study impact of Hurricane Opal on Florida coast, *Eos Trans. AGU, 77*(19), 181, 184.
Stone, G. W., P. Wang, D. A. Pepper, J. M. Grymes III, H. H. Roberts, X. Zhang, S. A. Hsu, and O. K. Huh (1999), Studying the importance of hurricanes to the northern Gulf of Mexico coast, *Eos Trans. AGU, 80*(27), 301, 305.
U.S. Army Corp of Engineers (1984), *Shore Protection Manual*, Vicksburg, Miss.
Walker, N. D., O. K. Huh, L. J. Rouse Jr., and S. P. Murray (1996), Evolution and structure of a coastal squirt off the Mississippi River delta: Northern Gulf of Mexico, *J. Geophys. Res.*, *101*(C9), 20,643–20,655.
Walker, N. D., R. R. Leben, and S. Balasubramanian (2005), Hurricane-forced upwelling and chlorophyll *a* enhancement within cold-core cyclones in the Gulf of Mexico, *Geophys. Res. Lett.*, *32*, L18610, doi:10.1029/2005GL023716.

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Sumatra Earthquake Research Indicates Why Rupture Propagated Northward

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The Sumatra earthquake of 26 December 2004 ($M_w = 9.3$) was one of the largest megathrust earthquakes ever recorded using a modern seismic network. The rupture initiated around 3°N near Simeulue Island and propagated northward for about 1250 kilometers up to the Andaman Islands. Nearly three months later, on 28 March 2005, a second large earthquake occurred ($M_w = 8.6$) about 150 kilometers farther southeast.

The aftershocks of these two events (Figure 1) do not overlap, with one lying east and the other west of Simeulue Island. This observation, along with modeling studies [*Lay et al.*, 2005; *Ammon et al.*, 2005] of the earthquake ruptures suggest that there should be a lithosphere-scale boundary around Simeulue, which could be either in the lower plate or in the upper plate. Such a boundary will act as a barrier for rupture propagation from an earthquake initiated on the other side of the boundary.

New results show that the lithospheric-scale boundary starts near Simeulue Island, continues up to the east of the Nicobar Islands and joins the Sumatra Fault in the north. The 26 December earthquake rupture might have initiated just west of this boundary near Simeulue Island; therefore, it did not cross the boundary towards east but propagated northwards up to the Andaman Islands.

By S. C. Singh

The channeling of the earthquake rupture in a narrow zone between the trench and this boundary may explain the large size of the 26 December event ($M_w = 9.3$) and the associated large tsunami. If stress is being accumulated along this boundary, then a major earthquake may occur along it in the near future (years to decades).

In order to understand the relationship between the source region at depth and deformation on the seafloor, the Sumatra-Andaman Great Earthquake Research Initiative (SAGER) is conducting a series of marine experiments offshore of west Sumatra. This research initiative was launched by the Institut de Physique du Globe de Paris (IPGP) after the earthquake, and involves 50 scientists associated with more than 15 international institutions, and industry partners.

West Andaman Fault

The first SAGER experiment, Sumatra-Aftershocks, was carried out from 15 July to 9 August 2005, on the French research vessel *Marion Dufresne*. Initial results indicate the presence of an active strike-slip fault, the West Andaman Fault (WAF), which might be a reactivated lithospheric boundary. This boundary could have channelled the rupture propagation northward during the 26 December earthquake and subsequently acted as a barrier for the 28 March earthquake rupture.

Swath bathymetry, imagery, and 3.5-kHz echosounder data were collected in a 380 × 80 square kilometer area that extends from the Sunda Trench in the Indian Ocean to the north of the Sumatra Fault (SF) (Figure 2). An active feature was found on the western flank of the Aceh fore-arc basin that seems to be connected with the WAF in the north. It is clearly visible for about 200 kilometers, but one can follow it for about 400 kilometers, close to the trench southwest of Simeulue. The feature could be an extension of the WAF in the south.

The feature is segmented on the scale of tens of kilometers into restraining and releasing bends leading to compressive and extensive regimes along the fault, suggestive of a right lateral strike-slip motion. The feature's azimuth varies from 345° in the north to 325° close to Simeulue as it approaches the trench. It is very likely that the WAF is bifurcated into different small segments as it approaches the trench, but the present data do not permit the imaging of these segments. In the north, the WAF joins with the SF around 7°30'N, and seems to be connected with the Eastern Margin Fault, the Sagaing Fault in Myanmar through a set of back-arc spreading centers, and transform faults in the Andaman Sea [*Curry*, 2005] (Figure 1).

The freshness of the fault trace and 3.5-kHz data suggest that the WAF has been active recently and could be a reactivated lithospheric boundary (Figure 2). Two strike-slip aftershocks occurred close to the WAF within the first few days after the 26 December event, and the northern branch of the WAF (7°–10°N) seems to have been very active (Figure 1a).

Reactivated Plate Boundary

Historical seismicity also shows the occurrence of strike-slip earthquakes along the WAF (Figure 1b), suggesting that the fault has been active for the last thirty years. The exact age of the WAF is difficult to determine, but it has been suggested that it existed around 30 million years ago [*Curry*, 2005]. Seismic reflection

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